Charm CP Violation

Stefan Schacht

Cornell

Brookhaven Forum 2019

Brookhaven National Laboratory
Upton, NY USA
September 2019

based on Y. Grossman and StS, JHEP 1907 (2019) 020 [1903.10952]

The Discovery of Direct Charm CP Violation

$$\Delta A_{CP} \approx \Delta a_{CP}^{\text{dir}} \equiv a_{CP}^{\text{dir}}(D^0 \to K^+K^-) - a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-)$$

Results

[PRL 122 (2019) 211803]

ΔA_{CP} [10^{-4}]	
-18.2 ± 3.2 (stat) ± 0.9 (syst)	π tagged (Run 2)
-9 ± 8 (stat) ± 5 (syst)	μ tagged (Run 2)
-10 ± 8 (stat) ± 3 (syst)	π tagged (Run 1) [PRL 116 (2016) 191601]
-14 ± 16 (stat) ± 8 (syst)	μ tagged (Run 1) [JHEP 07 (2014) 041]
$\boxed{-15.4 \pm 2.9 \text{ (stat+syst)}}$	combined

5.3σ deviation from zero

first observation of *CP* violation in charm

17

courtesy Angelo di Canto

Direct CP Violaton is an Interference Effect

$$a_{CP}^{\mathrm{dir}}(f) \equiv \frac{|\mathcal{A}(D^0 \to f)|^2 - |\mathcal{A}(\overline{D}^0 \to f)|^2}{|\mathcal{A}(D^0 \to f)|^2 + |\mathcal{A}(\overline{D}^0 \to f)|^2} \approx 2(r \sin\phi)\,(a\ \sin\delta)$$

for a decay amplitude (f = CP-eigenstate)

$$\mathcal{A} = 1 + r\,a\,e^{i(\phi+\delta)}$$

- r real and depends on CKM matrix elements,
- ϕ weak phase,
- a real ratio of the respective hadronic matrix elements,
- δ strong phase.

Why is Charm challenging for Theory?

- Physics is about small parameters we expand in.
- In Charm there is none.
- Intermediate mass compared to Λ_{QCD} : Not heavy, not light.
- Do methods like Heavy Quark Expansion and Factorization work?
- Need to find new ways to make predictions
  and play the game of QCD.
- That makes life more interesting.

Why was CP Violation so hard to find? Because it enters only via small non-unitarity!

- The external quarks involve only first two generations.
- 2x2 submatrix of CKM approximately unitary.

$$\begin{pmatrix} V_{ud} & V_{us} \\ V_{cd} & V_{cs} \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda \\ -\lambda & 1 \end{pmatrix},$$

$$V_{cd}^* V_{ud} \approx -V_{cs}^* V_{us} \approx -\lambda \,.$$

- CP violation in charm from small nonunitarity of 2x2 submatrix:

Misalignment: $V_{cd}^* V_{ud} + V_{cs}^* V_{us} = \Delta \,.$

- Charm can be described in an effective two-generational theory.
- In the SM, non-unitarity enters via 3rd generation:

$$\Delta = -V_{cb}^* V_{ub} \,, \qquad |\lambda| \gg |V_{cb}^* V_{ub}| \,.$$

CP Violation from non-unitarity of 2x2 submatrix of CKM

$$\mathcal{A}^{\mathrm{SCS}} = \lambda\, \mathcal{A}_{sd} + \frac{\Delta}{2}\mathcal{A}_r\,,$$

$$a_{CP}^{\mathrm{dir}} \equiv \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2} = -\mathrm{Im}\frac{\Delta}{\lambda}\mathrm{Im}\frac{\mathcal{A}_r}{\mathcal{A}_\Sigma}$$

Where does the non-unitary interference come from?

Comparison of Charm and B Physics

Reminder on B physics

- CP violation in B-physics comes from interference tree + penguin loop
- The top in the penguin loop is totally offshell.
- Penguin loop depends on $m_t/m_W > 1$.

Charm is different

- In charm decay, penguin operator is very small and irrelevant.
- Penguin loop depends on $m_b/m_W \ll 1$.
- Very strong GIM mechanism.

Charm CP violation is not about the penguin.

So, where does the interference come from?

$$D^0 \to \pi^+\pi^-$$
$$D^0 \to K^+K^-$$

$KK \leftrightarrow \pi\pi$ rescattering into same final state.

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^- \xrightarrow{\text{QCD}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^- \xrightarrow{\text{QCD}} K^+K^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^-$$

Thereby interference of trees with $V_{cs}^* V_{us}$ and $V_{cd}^* V_{ud}$.

CP violation $\propto V_{cs}^* V_{us} + V_{cd}^* V_{ud} = \Delta$.

$KK \leftrightarrow \pi\pi$ rescattering into same final state.

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^- \xrightarrow{\text{QCD}} \pi^+\pi^-$$

$$D^0 \xrightarrow{V_{cd}^* V_{ud}} \pi^+\pi^- \xrightarrow{\text{QCD}} K^+K^-$$

$$D^0 \xrightarrow{V_{cs}^* V_{us}} K^+K^-$$

We will see that rescattering is $\mathcal{O}(1)$, not small.

Charm CPV small because of small weak phase.

(not because of small rescattering.)

CP Violation in B vs. D

Beauty	Charm
Tree + Penguin	Tree + Rescattering
	
penguin	no penguin

Our point is: Talking about penguins in charm is misleading.

$SU(3)_F$ symmetry and Flavor Structure of Operators

- Approximate symmetry from $m_{u,d,s} \ll \Lambda_{\text{QCD}}$.
- QCD approx. invariant under unitary rotations of $(u,\, d,\, s)$.
- Correlations and sum rules between various charm decays.
- SU(2) ⊂ $SU(3)_F$ connecting u, d (Isospin) and d, s (U-spin).

U-spin Flavor Structure of Hamiltonian for SCS Decays

$$Q^{\bar{s}s} = (\bar{s}u)(\bar{c}s) \qquad Q^{\bar{d}d} = (\bar{d}u)(\bar{c}d)$$

$$Q^{\Delta U=1} = \frac{Q^{\bar{s}s} - Q^{\bar{d}d}}{2} \qquad Q^{\Delta U=0} = \frac{Q^{\bar{s}s} + Q^{\bar{d}d}}{2}$$

$$\mathcal{H}_{\text{eff}} \sim \underbrace{\frac{V_{cs}^* V_{us} - V_{cd}^* V_{ud}}{2}}_{\approx\, \lambda} Q^{\Delta U=1} + \underbrace{\frac{V_{cs}^* V_{us} + V_{cd}^* V_{ud}}{2}}_{=\, \frac{\Delta}{2}} Q^{\Delta U=0}$$

This talk: What do we learn from the new result?

[Grossman StS 1903.10952]

Direct CP asymmetries in SCS Charm decays

$$a_{CP}^{\mathrm{dir}} \equiv \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2} = \underbrace{-\mathrm{Im}\frac{\Delta}{\lambda}}_{= r \sin\phi} \times \underbrace{\mathrm{Im}\frac{A_r}{A_{sd}}}_{= a \sin\delta} .$$

(weak phase) (strong phase)

$$\text{SM: } -\mathrm{Im}\frac{\Delta}{\lambda} = \mathrm{Im}\frac{V_{cb}^* V_{ub}}{\lambda} = -6 \cdot 10^{-4}.$$

- The new measurement allows for the first time to explore the amplitudes of charm decays that are beyond the approximate two-generational unitarity of the CKM-matrix.
- $\Rightarrow$ Im($\Delta U = 0$ over $\Delta U = 1$ matrix elements).

Overview: Implications of $\Delta a_{CP}^{\mathrm{dir}}$

- The $\Delta U = 0$ rule.

- Comparison to $\Delta I = 1/2$ rules in K, D and B decays.

The $\Delta U = 0$ rule

Parametrize ratio of $\Delta U = 0$ over $\Delta U = 1$ matrix elements

The numerical result

$$\mathcal{A}(D \to KK) = \lambda\, t_0 - \lambda_b\, p_0$$

$$\Delta a_{CP}^{\mathrm{dir}} = 4\,\mathrm{Im}\left(\frac{\lambda_b}{\lambda}\right) |\tilde{p}_0| \sin(\delta_{\mathrm{strong}}) \,,$$

$$|\tilde{p}_0| \sin(\delta_{\mathrm{strong}}) = 0.65 \pm 0.12 \,.$$

Group theory language of $\tilde{p}_0 = p_0/t_0$

- t_0 : matrix element of $Q^{\Delta U=1} = (Q^{\bar{s}s} - Q^{\bar{d}d})/2.$
- p_0 : matrix element of $Q^{\Delta U=0} = (Q^{\bar{s}s} + Q^{\bar{d}d})/2.$

Decomposition into "no QCD" part, plus corrections

$$\tilde{p}_0 = B + Ce^{i\delta} \,.$$

- B: short-distance. $Ce^{i\delta}$: long distance.
- b quark in the loop perturbative, quarks lighter than the charm are not.

$$B = 1$$
$$\tilde{p}_0 = B + Ce^{i\delta}$$

- Perturbatively, diagrams with intermediate b are negligible.
- The limit $C = 0$ (i.e. no LD contribution to $\tilde{p}_0$) corresponds to only $Q^{\bar{s}s}$ can produce K^+K^- and only $Q^{d\bar{d}}$ can produce $\pi^+\pi^-$:

$$\langle K^+K^- | Q^{\bar{d}d} | D^0 \rangle = \langle \pi^+\pi^- | Q^{\bar{s}s} | D^0 \rangle = 0\,,$$

and

$$\langle K^+K^- | Q^{\bar{s}s} | D^0 \rangle \neq 0\,, \qquad \langle \pi^+\pi^- | Q^{\bar{d}d} | D^0 \rangle \neq 0\,.$$

We then see that $B = 1$ since

$$\frac{\langle K^+K^- | Q^{\Delta U=0} | D^0 \rangle}{\langle K^+K^- | Q^{\Delta U=1} | D^0 \rangle} = 1\,.$$

- That means in the no QCD limit $\tilde{p}_0 = 1$.

$$\delta = \mathcal{O}(1)$$
$$\tilde{p}_0 = 1 + Ce^{i\delta}$$

- Non-perturbative effects involve on-shell particles, giving rise to large strong phases to the LD effects independent of the magnitude of the LD amplitude.
- Rescattering can always give $\mathcal{O}(1)$ phases.

It follows, with $\sin\delta = \mathcal{O}(1)$:

$$\Delta a_{CP}^{\mathrm{dir}} = 4\,\mathrm{Im}\left(\frac{\lambda_b}{\Sigma}\right) \times C \times \sin\delta$$

Different predictions depending on size of corrections to no QCD limit C in

$$\tilde{p}_0 = 1 + Ce^{i\delta}\,, \qquad \Rightarrow \mathrm{Im}(\tilde{p}_0) = C\sin\delta.$$

What is C ?

$$\tilde{p}_0 = 1 + Ce^{i\mathcal{O}(1)}$$

Options

1. $C = \mathcal{O}(\alpha_s/\pi)$: Perturbative corrections to $\tilde{p}_0$.
2. $C = \mathcal{O}(1)$: Non-perturbative corrections that produce strong phases from rescattering but do not significantly change the magnitude of $\tilde{p}_0$.
3. $C \gg \mathcal{O}(1)$: Large non-perturbative effects with significant magnitude changes and strong phases from rescattering to $\tilde{p}_0$.

- (2) and (3) in principle not different: Both are non-perturbative.
- Value $\Delta a_{CP}^{\text{dir}} = 1 \times 10^{-4}$ corresponds to $C \sim 0.04$. (Assuming $O(1)$ strong phase.)
- **If** strong argument for C must be of category (1) $\Rightarrow$ New Physics.

The $\Delta U = 0$ rule

The $\Delta U = 0$ rule in charm

- With current data, C is consistent with category (2).
- SM picture: measurement of $\Delta a_{CP}^{\mathrm{dir}}$ proves the non-perturbative nature of the $\Delta U = 0$ matrix elements with a mild enhancement from $\mathcal{O}(1)$ rescattering effects. This is the $\Delta U = 0$ rule for charm.

What to do next, to learn more about the $\Delta U = 0$ rule in charm?

- Future data on phases δ_{KK} and $\delta_{\pi\pi}$ gives the phase δ in $\tilde{p}_0 = 1 + Ce^{i\delta}$.
- With that it will be possible to completely determine the characteristics of the emerging $\Delta U = 0$ rule.

Comparison to $\Delta I = 1/2$ rules in K, D and B decays

The $\Delta I = 1/2$ rule in Kaon Physics

Isospin decomposition of $K \to \pi\pi$ decays.

$$\mathcal{A}(K^+ \to \pi^+\pi^0) = \frac{3}{2} A_2^K e^{i\delta_2^K}$$

$$\mathcal{A}(K^0 \to \pi^+\pi^-) = A_0^K e^{i\delta_0^K} + \sqrt{\frac{1}{2}} A_2^K e^{i\delta_2^K}$$

$$\mathcal{A}(K^0 \to \pi^0\pi^0) = A_0^K e^{i\delta_0^K} - \sqrt{2} A_2^K e^{i\delta_2^K}$$

[Gell-Mann Pais 1955, Gell-Mann Rosenfeld 1957, Gaillard Lee 1974, Bardeen Buras Gerard 1987, Buras Gerard Bardeen 2014. Lattice: RBC-UKQCD 2012, Blum Boyle Christ Garron Goode 2011, 2012]

Data: $\Delta I = 1/2$ rule: category (3)

- $A_0^K / A_2^K = 22.35$ $\quad\quad$ $\delta_0^K - \delta_2^K = (47.5 \pm 0.9)^\circ$
- Non-perturbative rescattering affects not only the phases but also the magnitudes of the corresponding matrix elements.

The $\Delta I = 1/2$ rule in Kaon Physics, Contd.

Parametrization as "no QCD" plus corrections for K, D and $B \to \pi\pi$

$$A_0/A_2 = B + Ce^{i\delta}$$

- Limit of "no QCD": Only Q_2 contributes, [Buras 1989]

$$B = \sqrt{2}\,.$$

- Corresponds to $\tilde{p}_0 = 1$ in "no QCD" limit for $\Delta U = 0$ rule.

$$\Rightarrow C \gg \mathcal{O}(1)\,.$$

$\Delta I = 1/2$ Rule in K, D and B Decays

no QCD limit: $A_0^P / A_2^P = \sqrt{2} \approx 1.4$ [Buras 1989]

	Kaon	Charm	Beauty
Data	22	2.5	1.5
Enhancement	$\mathcal{O}(10)$	$\mathcal{O}(1)$	$\mathcal{O}(\alpha_s)$

[D: Franco Mishima Silvestrini 2012, B: Grinstein Pirtskhalava Stone Uttayarat 2014]

- Understand differences from mass scales governing K, D, B decays.
- Rescattering effects most important in K decays, less important but still significant in D decays, and small in B decays.

- We claim $\Delta U = 0$ follows a similar pattern. Both due to rescattering.

Other Approaches

Other approaches: Attemps to estimate rescattering.

- C = correction to no-QCD limit in $\frac{(\Delta U=0)}{(\Delta U=1)} = 1 + Ce^{i\delta}$.
- All agree that perturbative b-penguin is negligible.

Ref.	Method/Assumptions	C	NP or SM?
[Grossman StS 1903.10952]	Analogy to $\Delta I = 1/2$ rules	$\mathcal{O}(1)$	SM
[Brod Kagan Zupan 1111.5000]	QCDF/SCET, $1/m_c$ expansion	$\mathcal{O}(1)$	SM
[Soni 1905.00907]	$f_0(1710)$ resonance	$\mathcal{O}(1)$	SM
[Petrov Khodjamirian 1706.07780]	LCSRs (nonperturbative)	$\mathcal{O}(\alpha_s/\pi)$	NP or SM only param. errors
[Chala Lenz Rusov Scholtz 1903.10490]	update LCSRs + estimate for duality violation and other errors	$\mathcal{O}(\alpha_s/\pi)$	NP

Test case: Apply methods to $\Delta I = 1/2$ rule in charm.

Conclusions 1/2

- The recent discovery of CP violation in charm decays opens a whole new field, as we are now ready to explore CP violation in regions we did not have access to before.

- This will teach us more about New Physics and QCD.

- It is yet hard to be convinced that BSM physics is required.

- Assuming it is SM, we learn about QCD:
  Moderate non-perturbative effect, nominal $SU(3)_F$ breaking.

- We need $\Sigma a_{CP}^{\mathrm{dir}}$ and time-dependent measurements.

What to take home about Charm CP violation:

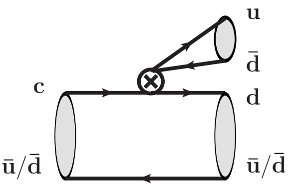
Beauty	Charm
Tree + Penguin	Tree + Rescattering
	
penguin	no penguin

Our point is: Talking about penguins in charm is misleading.

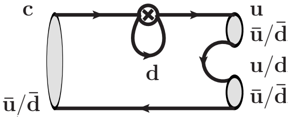
BACK-UP

Other Names for Rescattering in the Literature

- “Penguin topology”
- ”Penguin contraction of tree operator”



Tree



Rescattering

The Discovery of Direct Charm CP Violation

[LHCb, 1903.08726]

First Observation of CP Violation in Charmed Hadrons by LHCb

$\Delta A_{CP} = (-0.154 \pm 0.029)\%$, 5.3σ from zero.

$$\begin{aligned}\Delta a_{CP}^{\mathrm{dir}} &\equiv a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) - a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) \\ &= (-0.156 \pm 0.029)\%\end{aligned}$$

$$a_{CP}^{\mathrm{dir}}(f) \equiv \frac{|\mathcal{A}(D^0 \to f)|^2 - |\mathcal{A}(\overline{D}^0 \to f)|^2}{|\mathcal{A}(D^0 \to f)|^2 + |\mathcal{A}(\overline{D}^0 \to f)|^2}\,, \qquad (f = \text{CP-eigenstate})$$

HFLAV Update Moriond 2019

$$\Delta a_{CP}^{\mathrm{dir}} = (-0.164 \pm 0.028)\%$$

Completely general U-spin SM parametrization

U-spin quartet of $D \to P^+P^-$

[Brod Grossman Kagan Zupan 2012]

$$\mathcal{A}(K\pi) = V_{cs}V_{ud}^* \left(t_0 - \frac{1}{2}t_1\right),$$

$$\mathcal{A}(\pi\pi) = -\lambda\left(t_0 + s_1 + \frac{1}{2}t_2\right) - V_{cb}V_{ub}^* \left(p_0 - \frac{1}{2}p_1\right),$$

$$\mathcal{A}(KK) = \lambda\left(t_0 - s_1 + \frac{1}{2}t_2\right) - V_{cb}V_{ub}^* \left(p_0 + \frac{1}{2}p_1\right),$$

$$\mathcal{A}(\pi K) = V_{cd}V_{us}^* \left(t_0 + \frac{1}{2}t_1\right).$$

- Subscript = level of U-spin breaking, if power-counting switched on.
- Parametrization completely general: Independent from U-spin.
- Mainly interested in ratios:

$$\tilde{t}_1 \equiv \frac{t_1}{t_0}, \quad \tilde{t}_2 \equiv \frac{t_2}{t_0} \in \mathbb{R}, \quad \tilde{s}_1 \equiv \frac{s_1}{t_0} \in \mathbb{R}, \quad \tilde{p}_0 \equiv \frac{p_0}{t_0}, \quad \tilde{p}_1 \equiv \frac{p_1}{t_0}.$$

- 8 real parameters and 8 observables: system exactly solvable.

Branching ratio measurements (3 observables)

$$|A_\Sigma(KK)|^2 = \frac{\mathcal{B}(\bar{D}^0 \to K^+K^-))}{|\Sigma|^2 \mathcal{P}(D^0, K^+, K^-)}\,, \qquad |A_\Sigma(\pi\pi)|^2 = \frac{\mathcal{B}(\bar{D}^0 \to \pi^+\pi^-)}{|\Sigma|^2 \mathcal{P}(D^0, \pi^+, \pi^-)}\,,$$

$$|A(K\pi)|^2 = \frac{\mathcal{B}(\bar{D}^0 \to K^+\pi^-)}{|V_{cs}V_{ud}^*|^2 \mathcal{P}(D^0, K^+, \pi^-)}\,, \qquad |A(\pi K)|^2 = \frac{\mathcal{B}(\bar{D}^0 \to K^-\pi^+)}{|V_{cd}V_{us}^*|^2 \mathcal{P}(D^0, K^-, \pi^+)}\,.$$

- Neglect the tiny effects of order $|\lambda_b/\Sigma|$.

$$R_{K\pi} \equiv \frac{|\mathcal{A}(K\pi)|^2 - |\mathcal{A}(\pi K)|^2}{|\mathcal{A}(K\pi)|^2 + |\mathcal{A}(\pi K)|^2} = -0.11 \pm 0.01\,,$$

$$R_{KK,\pi\pi} \equiv \frac{|\mathcal{A}(KK)|^2 - |\mathcal{A}(\pi\pi)|^2}{|\mathcal{A}(KK)|^2 + |\mathcal{A}(\pi\pi)|^2} = 0.534 \pm 0.009\,,$$

$$R_{KK,\pi\pi,K\pi} \equiv \frac{|\mathcal{A}(KK)|^2 + |\mathcal{A}(\pi\pi)|^2 - |\mathcal{A}(K\pi)|^2 - |\mathcal{A}(\pi K)|^2}{|\mathcal{A}(KK)|^2 + |\mathcal{A}(\pi\pi)|^2 + |\mathcal{A}(K\pi)|^2 + |\mathcal{A}(\pi K)|^2} = 0.071 \pm 0.009\,.$$

Strong phase which does not require CPV (1 observable)

- Can be obtained from time-dependent measurements.
- Or correlated $D^0\bar{D}^0$ decays at a charm-τ factory.

Both methods: Strong phase between the CF and DCS decay modes.

$$\delta_{K\pi} \equiv \arg\left(\frac{\mathcal{A}(\bar{D}^0 \to K^-\pi^+)}{\mathcal{A}(D^0 \to K^-\pi^+)}\right) = \arg\left(\frac{\mathcal{A}(D^0 \to K^+\pi^-)}{\mathcal{A}(D^0 \to K^-\pi^+)}\right) = \left(8.6^{+9.1}_{-9.7}\right)^\circ \ .$$

[Grossman Kagan Nir 2006, Browder Pakvasa 1995, Wolfenstein 1995, Falk Nir Petrov 1999, Gronau Rosner 2000, Bergmann Grossman Ligeti Nir Petrov 2000, Falk Grossman Ligeti Petrov 2001, Bigi Sanda 1986, Xing 1996, Gronau Grossman Rosner 2001]

Integrated direct CP asymmetries (2 observables)

$$\Delta a_{CP}^{\rm dir} \equiv a_{CP}^{\rm dir}(D^0 \to K^+K^-) - a_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$$
$$= -0.00164 \pm 0.00028 \qquad \text{(HFLAV)}\,,$$

$$\Sigma a_{CP}^{\rm dir} \equiv a_{CP}^{\rm dir}(D^0 \to K^+K^-) + a_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$$
$$= 0.002 \pm 0.002\,.$$

(our result from HFLAV av. of $A_{CP}(D^0 \to K^+K^-)$ and $A_{CP}(D^0 \to \pi^+\pi^-)$)

[Einhorn Quigg 1975, Abbott Sikivie Wise 1980, Golden Grinstein 1989, Brod Grossman Kagan Zupan 2012, Franco Mishima Silvestrini 2012, Hiller Jung StS 2012, Mller Nierste StS 2015, Buccella Lusignoli Miele Pugliese Santorelli 1994, Grossman Kagan Nir 2006, Artuso Meadows Petrov 2008, Khodjamirian Petrov 2017, Cheng Chiang 2012, Feldmann Nandi Soni 2012, Li Lu Yu 2012, Atwood Soni 2012, Grossman Robinson 2012, Buccella Paul Santorelli, 2019, Yu Wang Li, 2017, Brod Kagan Zupan 2011]

Strong phases that require CP violation (2 observables)

[e.g. Gronau Grossman Rosner 2001, Nierste StS 2015]

$$\delta_{KK} \equiv \arg\left(\frac{\mathcal{A}(\bar{D}^0 \to K^+K^-)}{\mathcal{A}(D^0 \to K^+K^-)}\right), \qquad \delta_{\pi\pi} \equiv \arg\left(\frac{\mathcal{A}(\bar{D}^0 \to \pi^+\pi^-)}{\mathcal{A}(D^0 \to \pi^+\pi^-)}\right).$$

- Relative phases of the amplitudes of a $\bar{D}^0$ and D^0 going into one of the CP eigenstates.
- Can be obtained from time-dependent measurements or measurements of correlated $D^0\bar{D}^0$ pairs.

The system is exactly solvable.

For application to current data use U-spin power counting

Examples:

$$R_{K\pi} = -\mathrm{Re}(\tilde{t}_1)(1 + \mathcal{O}(\varepsilon^2))\,,$$
$$R_{KK,\pi\pi} = -2\,\tilde{s}_1\,(1 + \mathcal{O}(\varepsilon^2))\,,$$

$$\Delta a_{CP}^{\mathrm{dir}} = \mathrm{Im}\left(\frac{\lambda_b}{\Sigma}\right) \times 4\,\mathrm{Im}\,(\tilde{p}_0)\,(1 + \mathcal{O}(\varepsilon^2))\,,$$

and

$$\Sigma a_{CP}^{\mathrm{dir}} = 2\mathrm{Im}\left(\frac{\lambda_b}{\Sigma}\right) \times [2\,\mathrm{Im}(\tilde{p}_0)\tilde{s}_1 + \mathrm{Im}(\tilde{p}_1)]\left(1 + \mathcal{O}(\varepsilon^2)\right)\,.$$

- Relations to parameters only get relative correction at order $\mathcal{O}(\varepsilon^2)$.

Numerical Results

$$\mathrm{Re}(\tilde{t}_1) = 0.109 \pm 0.011\,,$$
$$\mathrm{Im}(\tilde{t}_1) = -0.15^{+0.16}_{-0.17}\,,$$
$$\tilde{s}_1 = -0.2668 \pm 0.0045\,,$$
$$-\frac{1}{4}\,(\mathrm{Im}\tilde{t}_1)^2 + \mathrm{Re}(\tilde{t}_2) = 0.075 \pm 0.018\,, \qquad \mathrm{Im}\,\tilde{p}_0 = -0.65 \pm 0.12\,,$$

$$2\mathrm{Im}(\tilde{p}_0)\tilde{s}_1 + \mathrm{Im}(\tilde{p}_1) = 1.7 \pm 1.6\,.$$

1. $\tilde{p}_1$ is the least constrained parameter: basically no information. Learn more: $\Sigma a_{CP}^{\mathrm{dir}}$, δ_{KK} and $\delta_{\pi\pi}$.
2. The higher order U-spin breaking parameters consistently smaller than the first order ones.
3. Second order ones even smaller: U-spin expansion works.
4. $SU(3)_F$ breaking of tree smaller than broken penguin.
5. Rough estimate: $\mathcal{O}(\varepsilon^2)$ in $\Delta a_{CP}^{\mathrm{dir}}$ is $\sim 10\%$. Need knowledge of $\tilde{p}_1$.

$\Delta I = 1/2$ enhancement much larger than $\Delta U = 0$ one. So why is Kaon direct CPV smaller than Charm direct CPV?

Write amplitudes very generically up to a normalization

$$\mathcal{A} = 1 + r\, a\, e^{(i\phi+\delta)}\,,$$

- r real and depends on CKM matrix elements,
- a real ratio of the respective hadronic matrix elements.
- For kaons a is ratio of matrix elements of $Q^{\Delta I=1/2}$ over $Q^{\Delta I=3/2}$.
- For charm a is ratio of matrix elements of operators $Q^{\Delta U=0}$ over $Q^{\Delta U=1}$.

$\Delta I = 1/2$ rule reduces CPV, $\Delta U = 0$ rule enhances CPV

Limit of two generations

$$\mathcal{A}_{\text{Kaon}} = V_{us} V_{ud}^* \left(A_{1/2} + r_{\text{Clebsch}} A_{3/2} \right),$$
$$\mathcal{A}_{\text{Charm}} = V_{cs} V_{us}^* A_1 .$$

Switch on Third generation

- Nonunitarity of 2×2 CKM induces small correction.
- $|r_{\text{Kaon}} - 1| \ll 1$ and $r_{\text{Charm}} \ll 1$.
- Kaon weak phase from SD penguins with $V_{ts} V_{td}^*$
- Both cases: $\delta \sim \mathcal{O}(1)$ from non-perturbative rescattering.

$$A_{CP} = -\frac{2ra\sin(\delta)\sin(\phi)}{1 + (ra)^2 + 2ra\cos(\delta)\cos(\phi)} \approx \begin{cases} 2r\,a\, \sin(\delta)\sin(\phi) & , r\,a \ll 1 \text{ (charm)}, \\ 2(ra)^{-1} \sin(\delta)\sin(\phi) & , r\,a \gg 1 \text{ (kaons)}. \end{cases}$$

- For $ra \ll 1$ increasing a gives enhancement (charm).
- While for $ra \gg 1$ it is suppressed (kaons).